



Indian and Northern
Affairs Canada

Affaires indiennes
et du Nord Canada

Environmental Studies No. 22

Recovery of Arctic and Sub-Arctic Vegetation Nine Summers After Crude and Diesel Oil Spills



86-04725/

**Recovery of Arctic and
Sub-Arctic Vegetation Nine
Summers After Crude and
Diesel Oil Spills**

Northern Affairs Program

T.C. Hutchinson
Department of Botany and Institute for
Environmental Studies
University of Toronto

Published under the authority of the
Hon. David E. Crombie, P.C., M.P.,
Minister of Indian Affairs and
Northern Development,
Ottawa, 1984

QS-8358-000-EF-A1
Catalogue No. R71-19/22-1985E
ISBN 0-662-13799-X

This report was prepared under contract for the
Environmental Division, Northern Natural Resources
and Environmental Development. The views,
conclusions and recommendations expressed herein
are those of the author and not necessarily those of
the department.

TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE NO.</u>
1. SUMMARY	1
2. INTRODUCTION	3
2.1. Summary of 1972-1976 Studies on Short-term Effects of Oil Spills	4
3. METHODS	
3.1. Site Description	7
3.2. Application of Oil	7
3.3. Fertilizer Treatments	8
3.4. Data Collection	8
4. RESULTS AND DISCUSSION	
4.1 EFFECTS OF THE 1972-1975 OIL SPILLS ON MACKENZIE VALLEY BLACK SPRUCE TAIGA	
4.1.1. Norman Wells Burnt Forest Sites	10
4.1.1.1. Crude Oil Spills	10
4.1.1.1.1. Even 9.1 litre/m ² Spill	10
4.1.1.1.2. 8500 litre Point Spill (50 Barrel)	11
4.1.1.2. Diesel Oil Spill	11
4.1.1.3. Effect of Fertilizer Applications to Oil Spill Sites	12
4.1.2. Norman Wells Mature Forest Sites	12
4.1.2.1. Crude Oil Spills	12
4.1.2.1.1. Summer Spills	12
4.1.2.1.2. Winter Spills	12
4.2. EFFECTS OF THE 1972-1975 CRUDE OIL SPILLS ON LOW ARCTIC TUNDRA AT TUKTOYAKTUK	
4.2.1. Cotton-grass Tundra	13
4.2.1.1. Summer Spill: Effects on both fertilized and unfertilized quadrats	13
4.2.1.1. Winter Spill	14

Table of Contents (con.)

<u>SECTION</u>	<u>PAGE NO.</u>
4.2.2. Dwarf Shrub-lupine Tundra	14
4.3. EFFECTS OF SPILLS ON DEPTH OF ACTIVE LAYER	15
5. SOME RECENT FINDINGS FROM ALASKAN OIL FIELD STUDIES	17
6. REFERENCES	18
7. TABLES	20-28
8. FIGURES	29-32
9. PLATES	33-37
10. APPENDIX	38-39

LIST OF TABLES

<u>Table</u>	<u>Page No.</u>
1. Summary of oil spill type, location and date of spill.	20
2. Cover values of vegetation at the burnt forest site, Norman Wells, following crude and diesel oil spills,	21
3. Frequency values of vegetation at the burnt forest site, Norman Wells, following crude and diesel oil spills.	22
4. Cover values of vegetation at the mature forest site, Norman Wells, following summer and winter crude oil spills.	23
5. Frequency values of vegetation at the mature forest site, Norman Wells, following summer and winter crude oil spills.	24
6. Cover and frequency values of vegetation at the cotton-grass tundra site, Tuktoyaktuk, following summer and winter crude oil spills.	25
7. Number of species found per plot in the oiled and control plots at Norman Wells and Tuktoyaktuk.	26
8. Cover and frequency values of vegetation at the dwarf shrub-lupine site, Tuktoyaktuk, following summer and winter crude oil spills.	27
9. Mean depth of active thaw layer of sites at Norman Wells and Tuktoyaktuk.	28

LIST OF FIGURES

<u>Figure</u>	<u>Page No.</u>
1. Total plant cover of the burnt and mature forest sites at Norman Wells from 1972-1980.	29
2. Total percent frequency of the burnt and mature forest sites at Norman Wells from 1972-1980.	30
3. Total plant cover of the cotton-grass and dwarf shrub-lupine tundra sites at Tuktoyaktuk from 1972-1980.	31
4. Total percent frequency of the cotton-grass and dwarf shrub-lupine tundra sites at Tuktoyaktuk from 1972-1980.	32

LIST OF PLATES

<u>Plate</u>	<u>Page No.</u>
1. Crude oil summer spill site in the mature taiga at Norman Wells.	33
2. Diesel oil spill site in the burnt forest taiga at Norman Wells.	33
3. Crude oil winter spill in the mature taiga at Norman Wells, July 1973.	34
4. Crude oil winter spill in the mature taiga at Norman Wells, August 1980.	34
5. Control cotton-grass tundra site at Tuktoyaktuk.	35
6. Close-up of the winter oil spill site in the cotton-grass tundra at Tuktoyaktuk.	35
7. Overview of the winter spill site in the cotton-grass tundra at Tuktoyaktuk.	36
8. Close-up of the summer spill site in the cotton-grass tundra at Tuktoyaktuk.	36
9. Summer spill site in the dwarf shrub - lupine tundra at Tuktoyaktuk, June 1975.	37
10. Summer spill site in the dwarf shrub - lupine tundra at Tuktoyaktuk, August 1980.	37

ACKNOWLEDGEMENTS

Jeff Kaiser provided invaluable assistance in collecting field data at the spill sites during August 1980. Valuable logistic support was provided at Tuktoyaktuk by the Polar Continental Shelf Project. Valda Zobens greatly assisted in the development of the 1972-1976 data base at Norman Wells and Tuktoyaktuk, and Kersti Meema has helped greatly with editorial changes and preparation of this report.

RÉSUMÉ

En août 1980, on a déterminé le degré de rétablissement de la végétation soumise, entre 1972 et 1975, à des expériences de déversement estivaux et hivernaux d'hydrocarbures et les variations de la profondeur du dégel de la couche active, dans des placettes de la taiga à épinette, à Norman Wells, et de la toundra, à Tuktoyaktuk, dans les Territoires du Nord-Ouest.

Après 6 à 9 ans, les deux types de placettes portaient encore des traces très visibles des déversements. La principale cause en est le rétablissement en général très faible des lichens et des mousses qui constituent un pourcentage élevé de la flore des régions étudiées. Une autre observation frappante était qu'aucun semis ne s'était implanté depuis les déversements. Seuls avaient survécu les organes de réserve ou d'hibernation enfouis ou les bourgeons aériens protégés. Certains arbres comme l'épinette noire ont pris jusqu'à 4 ans pour mourir tandis que d'autres plantes comme la prêle et les mousses Hylocomium splendens, Tomenthypnum nitens et Polytrichum juniperinum ont souvent pris au moins 4 ans avant de donner des pousses vivantes. Invariablement, cette renaissance se faisait parmi des touffes mortes et exactement au même emplacement où se trouvaient les plantes avant le déversement. Ceci porte à croire que beaucoup de plantes d'origine n'ont pas été tuées, mais ont survécu sans feuille pendant un certain nombre d'années, par leurs parties enfouies.

Les déversements de brut exécutés l'été on constamment montré un effet réducteur plus fort à l'égard de la diversité des espèces et de la vitesse de rétablissement que les déversements exécutés en hiver, à la fois dans la taiga et dans la toundra. Souvent, seules très peu d'espèces parvenaient à se rétablir. Leur ralentissement était supérieur dans la toundra plutôt que dans la pessière. Les déversements exécutés l'hiver ont eu un effet qui était fortement déterminé par le volume épandu, malgré la dormance de la végétation au moment du déversement.

Les plantes naines, notamment le thé du Labrador, le bouleau et le saule, se sont révélées assez tolérantes. La linaigrette dense (Eriophorum vaginatum) était peut-être la plus tolérante de toutes les espèces. Arctagrostis arundinacea était une bonne colonisatrice des terrains contaminés.

La fertilisation a stimulé le rétablissement dans la toundra, mais non dans la pessière.

Dans cette dernière, le rétablissement suite à un déversement de combustible diesel a été plus rapide qu'à la suite d'un déversement équivalent de brut en été, surtout chez la mousse Tomenthypnum nitens, l'épinette noire, le mélèze et les saules.

En un endroit où on avait déversé 8 500 litres, la superficie de végétation morte s'est étendue depuis 1975, ce qui porte à croire que la toxicité a poursuivi son action dans le sous-sol. Toutefois, l'effet global de ce déversement ponctuel était encore de beaucoup inférieur à l'effet de volume équivalents pulvérisés uniformément sur la végétation.

L'effet nuisible et soutenu des déversements sur la végétation a aussi été mis en évidence par la profondeur du dégel du sol de surface, qui était supérieur de 70 p. 100 dans les placettes polluées au combustible diesel par rapport aux placettes témoins. Les déversements de brut à Norman Wells ont aussi augmenté la profondeur du dégel, avant 1980, comparativement aux parcelles témoins. Dans la toundra, on n'a observé aucune différence dans la profondeur du dégel entre les placettes soumises aux déversements et les témoins.

Les raisons de poursuivre ces études semblent très fortes : ces placettes d'expérimentation, dans des conditions déterminées, des effets des déversements sont celles qui sont établies depuis le plus longtemps, et le rétablissement, dans leur état d'origine, de la couverture végétale et de la diversité des espèces est encore, dans de nombreux cas, une éventualité lointaine.

1. SUMMARY

In August 1980 the experimental oil spill sites which had been set up in the spruce taiga at Norman Wells and on tundra at Tuktoyaktuk, N.W.T., from 1972-1975 were monitored to determine the degree of recovery of the vegetation from summer and winter spills and the changes in depth of active layer thaw.

After 6-9 years, the experimental oil spill sites in both tundra and taiga still showed very marked effects of the spills. A major factor in this is the generally very poor recovery of the lichens and mosses which constitute a high percentage of the flora of the regions studied. Another striking feature has been that no seedling establishment at all has occurred since the spills. All recovery has been from survival of below-ground storage or overwintering organs or from protected above-ground buds. While death of trees such as black spruce took up to 4 years to be complete, other plants such as the horsetail and the mosses Hylocomium splendens, Tomenthypnum nitens and Polytrichum juniperinum, often took 4 years or longer before any living shoots reappeared. These invariably appeared amidst dead tussocks and in exactly the same position of plants prior to the spill. This suggests that many of the original plants were not killed but survived for a number of years below-ground without leaves.

The crude oil summer spills continued to show greater species reduction and slower recovery than winter spills. This was true both on taiga and on tundra. The recovery which did occur was often dominated by just a very few species. Better recovery occurred on tundra sites than in the spruce forest. Winter spills were strongly influenced by the intensity of spill, despite the dormancy of the vegetation at the time of the spills.

Dwarf shrubs, especially labrador tea, birch and willow, had good abilities to recover from spills. Cotton-grass, Eriophorum vaginatum, was perhaps the most oil-tolerant of all species. Reed-bentgrass was a good invader of the contaminated sites.

Fertilizer additions had a stimulating effect on recovery of the tundra but not in the spruce forest.

The recovery at the diesel spill site was faster than at an equivalent summer crude oil spill site in the spruce forest. The moss Tomenthypnum nitens, black spruce, tamarack and willows were the major contributors.

At the 8500 litre point spill site the area of dead vegetation had increased since 1975, suggesting continued toxicity of oil in sub-surface layers. However, the overall effect of the point spill was still a good deal less than equal volumes of oil sprayed evenly onto vegetation.

The damaging and sustained effect on the vegetation was also reflected in depth of thaw of surface soil which was 70% greater in the diesel plots than in the controls. Crude oil spills at Norman Wells also caused a significantly greater depth of thaw by 1980 than in control plots. No significant differences in thaw depth were found between oiled and control plots on the tundra.

The case for continuing these studies appears very strong in that they are the longest running controlled experimental spill sites in existence and recovery to full vegetative cover and a return to species richness is still a long way off in several cases.

2. INTRODUCTION

Arctic oil developments on land and in the marine environment during the 1970's have raised concerns about the possible ecological consequences of oil spills in the arctic. Active oil wells have operated at Norman Wells, N.W.T., since the early 1920's and on the North Slope of Alaska since the late 1970's. In addition, a major pipeline now traverses Alaska from north to south, ending in Valdez, and innumerable pipelines operate in northern Alberta.

In 1970 virtually no information on the effects of arctic oil spills was available. Since then, intensive efforts have been made to develop predictive models for such spills under a wide variety of conditions. A good deal of the Canadian information has come from programmes of DINA associated with the proposed Mackenzie Valley pipeline. In connection with this proposed development we have carried out studies since 1972 on experimental oil spills. These spills were made onto terrestrial and freshwater ecosystems at Norman Wells and Tuktoyaktuk, at sites which are considered representative of large areas which the pipeline would have traversed. The new Norman Wells pipeline along the Mackenzie River cuts through long stretches of terrain like that onto which the experimental spills at Norman Wells were made.

Though monitoring of short-term effects of oil spills was an original objective, the intent ever since the studies were initiated has been to assess the effects of oil spills over the long term. Rarely are any long term ecological studies carried out, particularly in the arctic regions where our overall knowledge is very limited, though biologists consider them essential. The 1980 monitoring of the 1972-74 spill sites was an attempt to expand our knowledge of long-term effects on vegetational recovery.

The objectives of the 1980 monitoring remained essentially the same as those set out in 1972. These can be summarized as follows:

- a) To study short- and long-term effects of simulated crude oil spills on both terrestrial and aquatic vegetation, and on aquatic microfauna.
- b) To determine the range of responses by plants to seasonal oil spills, including the degree of sensitivity of individual species and their relative ability to recover following spills.
- c) To determine the ability of species to recolonize spill areas by sexual reproduction i.e. seeds, spores, etc., or by vegetative propagation.
- d) To compare the vegetational responses to crude oil and diesel spills.
- e) To assess the efficacy of fertilizer applications for speeding up recovery.
- f) To study the effect of oils spills on depth of thaw of surface layers (active layer).
- g) To compare winter and summer spill effects, and effects on tundra and taiga vegetation.
- h) To determine the persistence of phytotoxic components of oil in arctic soils following spills.

The chemical analysis of the soils collected in 1980 has been done as a separate contract to D. Mackay, Chemical Engineering, University of Toronto. This should allow us to relate observed features of plant recovery with changes in the oil residues in the soils.

The observations from the earlier studies (1972-1975) on this project are given in: Hutchinson and Hellebust, 1973, 1978; Hutchinson, Hellebust, and Telford, 1974, 1975; Hutchinson and Freedman, 1975, 1978; and Freedman and Hutchinson, 1976. This information will not be repeated here in detail. The aquatic studies were discontinued in 1975 and the terrestrial sites were not monitored between 1975 and 1980. The monitoring at Norman Wells in 1980 was, therefore, made in the 9th and 10th growing seasons following summer and winter spills, respectively; in Tuktoyaktuk it was in the 8th and 7th seasons following summer and winter spills, respectively.

2.1. SUMMARY OF 1972-1976 STUDIES ON SHORT-TERM EFFECTS OF OIL SPILLS

The most significant biological effect of experimental crude oil spillage on both tundra and taiga is the rapidity and extent of damage to photosynthesizing plant tissue. This damage is indicated by decreases in species' cover values, frequency and diversity. The unweathered crude oil acted as a contact herbicide killing almost all species of mosses and lichens and causing premature shedding of the foliage of higher plants. The summer spills were more devastating than the winter spills and regardless of the time of spillage less damage occurred in the tundra sites than in those of the taiga. Signs of regeneration, however, occurred quickly, so that within a few weeks after a spill regrowth of some species occurred.

Mosses and lichens, which contribute significantly to ground cover, are very sensitive to contact with oil and had shown little ability to recover or recolonize through 1975. They are particularly sensitive because they are non-rooting and lack a protective cuticle, thereby absorbing oil directly through surface cells. There was no recovery of these plants with the exception of the moss Polytrichum juniperum which produced new shoots from apparently dead plants 3 and 4 years after the spill. Interestingly, this moss is one of the few with a cuticular protective layer. Another of the non-flowering plants to show a delayed recovery was the horsetail Equisetum pratense, a common taiga species, which was totally defoliated by the spill but began to send up shoots in the 4th post-spill summer.

Of the flowering plants, the broad leaf deciduous species showed signs of damage most rapidly. The decreases in cover values, frequency and species diversity due to contact with oil are correlated with decreases in chlorophyll content of the foliage which had been sprayed. Initial defoliation, however, was not necessarily permanent. Taiga species which showed good ability to recover include dwarf birch, green alder, shrub willows and labrador tea; tundra species include dwarf willow, dwarf birch and cotton-grass. Invasion by "weedy" species, such as chickweed, reed-bentgrass, and fescue grass, also began in the year following the spills at the tundra sites. Fertilizer applications greatly accelerated this process and also stimulated cotton-grass. In the first 3 years after spills some plants, especially the dwarf shrubs, produced gigantic leaves with many times the surface area of normal leaves. This did not appear to be controlled by nutrition since fertilizer application produced more foliage rather than gigantic foliage. This gigantism is probably caused by the effect of hydrocarbons from the spill on plant growth hormones.

While severe damage occurred from summer spills, some regrowth from below-ground shoots took place in the summer in which the crude oil spills were made. However, the number of survivors and quantities of above-ground foliage was markedly reduced by the following summer. This winter-kill factor seemed crucial and may well relate to the inadequacy of storage reserves being built up following the oil spill thus causing defoliation. The plants do not have enough reserves to survive the long winter.

The initial tolerance of black spruce to oil contamination was not sustained in subsequent years. The trees survived well the first year though foliage was killed where contacted by oil. However, in the second year trees began to die; this continued for 4 years (1975) at which time all the spruce in the summer spill plots were dead. This gradual response may be caused by a combination of factors including: (1) the prolonged toxicity of oil or (2) mechanical interference of water uptake by roots due to the persistence of toxic hydrocarbons in the soil, the latter supported by foliar symptoms of drought, and (3) the general physiological weakening of trees, making them more susceptible to physical or biological stresses normally endured, such as, pathogens or winter stresses.

In contrast to the black spruce, the tamarack (larch) in the Norman Wells plots was killed directly as a result of summer spills. No surviving shoots were ever found. The winter spills had virtually no effect on tamarack. Since it is a deciduous tree it has no leaves in winter; thus, the contact herbicide effect was avoided.

The winter spill areas had less initial damage to plants than those of the summer spill. In addition, recovery was more rapid. The dormant, less susceptible condition of the plant and lack of foliage on the deciduous shrubs at the time of contact may be factors involved. Volatilization of low-boiling aromatics and alkanes (Mackay *et al*, 1974) and subsequent partial detoxification of the crude oil during the spring after the winter spillage may also contribute to the relative rapidity of recovery. By the time new leaves are produced in the spring and growth is resumed, the oil has been weathered and its toxicity is very much reduced.

Irrespective of the time of year of the spill, reproductive ability was severely reduced. Few species flowered or fruited during the three years after a spill, although improvement was noted with fertilizer applications to tundra sites, especially for cotton-grass. Reed-bent grass is a rather insignificant component of this community in the absence of fertilizer, but shows an excellent response in both productivity and reproductive capability when fertilizer was added.

Tundra vegetation was affected somewhat less severely than that of the taiga. This seemed to be due to the presence of a few very resistant species such as the shrub willow, Salix glauca, and cotton-grass, Eriophorum vaginatum, at the tundra sites, rather than a simple enhanced tolerance of all tundra species. Indeed, the large moss and lichen component of the tundra sites was virtually eliminated by both summer and winter crude oil spills.

Since a change in the depth of the active layer above the permafrost could lead to changes in terrain stability, and since this layer provides the essential nutrient and rooting layer, large differences in depth of active

layer between treatments would be significant. However, no consistent increases were noted in depth of the active layer. An initial 20-25% increase occurred in the burnt forest taiga site, but this difference was not maintained through 1975 from 1972.

The effects of oil spillage made by spraying were markedly more damaging than those of a 8500 litre point spill in terms of surface area per unit of oil applied. Topography is a factor in the extent of damage in a point spill because "islands" of vegetation located on higher ground were able to survive outside of the immediate central area of about 60m² where all vegetation was killed. However, large quantities of oil from the point spill appeared to still be present in toxic form 3 years after the spill; by the 4th year the affected area was greatly increased due to mobility of oil by heavy rains.

Diesel spills caused defoliation and reduced ground cover. They appear to have as a severe effect on vegetation in the short term as crude oils spills. In the long term, species survival is better in the diesel spill sites probably because in the absence of tarry compounds volatilization of toxic oil components is hastened.

Based on the rates of increase in foliar cover and on the continued death of black spruce some predictions of long-term recovery were made in 1975: a period in excess of 10 years would be necessary for the regeneration of a complete vegetative cover on the oil spill sites and that up to 20-30 years may be necessary. These estimates were reduced for the recovery of a winter spill site. Soil toxicity was clearly reduced so seedling establishment was confidently expected.

These were the major findings from the 1972-76 studies. The 1980 monitoring of the sites allows us to determine the longer term pattern of recovery and see how the predictions are holding up over time.

3. METHODS

3.1. Site Description

The sites chosen for experimental spills represent typical subarctic terrestrial environments in the Mackenzie Valley and low arctic tundra on the Tuktoyaktuk peninsula.

Mature forest and burnt forest taiga sites at Norman Wells, N.W.T., are representative of the Mackenzie Valley communities. The taiga typically consists of black spruce (*Picea mariana*) forest and is underlaid by permafrost. Because of the importance of naturally occurring fires in this area, spills were made both in mature forest with trees up to 10m tall which showed no signs of previous burns and in a previously burnt forest with trees of 2-3m (Hutchinson and Hellebust, 1973). The fire had occurred 35-40 years previously, as dated by annual growth rings of regenerated black spruce.

Two types of tundra vegetation near Tuktoyaktuk were chosen as being typical of the western low arctic tundra: a poorly drained cotton-grass, (*Eriophorum vaginatum*) meadow, and a better drained dwarf shrub (willow and birch) - arctic lupine tundra. The latter occurs very widely in the Mackenzie delta and is on soil of better base status than the acidic cotton-grass areas. At Tuktoyaktuk the dwarf shrub - lupine site is on a developing low pingo.

3.2. Application of Oil

The oil used for all spills was obtained from the Norman Wells oil field. Spills of crude oil were made, since it was anticipated that unrefined oil would be shipped by pipeline to southern refineries. In addition, a spill of Arctic Diesel oil was made on the burnt forest site at Norman Wells in 1975. This refined oil fraction is widely used and transported in the north and comparative information was required on its field toxicity by DINA. Most spills to date in arctic regions of Canada have been of diesel oil.

Since oil spills from pipeline rupture or from transportation accidents can occur at any time of the year, it was felt necessary to make spills in both summer, during the active growing season, and in the winter when the ground is still frozen, generally snow-covered, and the vegetation dormant.

Snow-melt and run-off occur in early to mid-May at Norman Wells in most years and slightly later at Tuktoyaktuk. Thus, winter spills made in February and early March in 1973 and 1974 had almost 3 months of weathering before plant growth commenced. Oil spilled in the winter has changed physical characteristics compared with summer spilled oil, especially in terms of spreading properties and volatilization. These changes were expected to reduce the toxicity of oil to plants.

Plots measuring 10m x 10m at each site were sprayed evenly with oil by hand pump and through a garden hose. The intensity of both the crude oil and diesel sprays was 9.1 litres per square metre, approximately 3 barrels per 100 square metres. Sprays were made at a height of 1.5 m above the ground. This produced a heavy wetting of all above ground surfaces and soaked the soil to a depth of a few centimetres. Although this method of oil application does not in any sense simulate spillage from a pipeline break, it does allow for a comparison of species' responses under controlled spill conditions. A less

intense spraying of 6.0 litres per square metre was also applied onto a second plot in the cotton-grass tundra at Tuktoyaktuk in the winter of 1973. In conjunction with D. Mackay, Dept. of Chemical Engineering, U. of Toronto, we also carried out a point spill of 8500 litres (50 barrels) of crude oil at a single discharge point in the burnt forest at Norman Wells in 1973.

Table 1 summarizes the oil treatments, locations and dates of spills.

3.3. FERTILIZER TREATMENTS

Fertilizer treatments were applied to summer spill and control plots at both Norman Wells and Tuktoyaktuk in August 1973. The major purpose was to determine whether the rates of vegetation recovery could be accelerated by fertilizer treatments. Applications were made only once onto two 2x10 m strips within the 10x10m experimental plots. The two fertilizer treatments used were 1) ammonium nitrate and 2) super-phosphate, and these plots were separated by unfertilized buffer zones. Applications were made after spills. The fertilizer was applied at a rate of 400 lbs per hectare.

3.4. Data Collection

All species growing at the sites were recorded in order to quantify their contribution to the plant associations occurring at the sites. The plot sizes used (10m x 10m) were large enough to account for most patterns of vegetation in the taiga and tundra vegetation studies. The cotton-grass sites at Tuktoyaktuk straddled a large series of raised centre ice polygons. The plots were also sufficiently large to overcome predominant 'edge' to area problems, and trampling effects. Nevertheless, trampling while recording data was an unavoidable factor. Large buffer areas were left between sites and control plots were set up for identical recording activity. In addition, untrampled areas were always recorded as virgin controls for collection of active layer depth at the same time as the plots.

Cover is a term widely used to describe the area on the ground occupied by a vertical projection downward of all foliage. Cover values were determined by randomly placing 50 'pins' of about 1 metre in length within the 10m x 10m plots and tabulating the number of times a vertically placed pin contacted a plant; the total number of contacts for a species was calculated as a percentage of the original 50 pins. Since foliage of several different species often overlap, and foliage of a single plant overlaps, a single pin may contact a number of different species or the same plant a number of times, resulting in a ≥ 100 percentage value. If each pin contacts, on average, two leaves at each placement, cover would be 200%. In effect, cover values thus determined give a measure of cover in 3-dimensions rather than in a two-dimensional plane.

Frequency, another means of describing vegetation, is a measure of the probability of finding a particular species in a quadrat. A species with a 50% frequency should occur in half of the quadrats. Therefore, a single species will always have a frequency of $< 100\%$ but the total frequency of all plants in an area may be $\geq 100\%$. If the combined estimated frequencies of all species in an area is 750%, then on average we would expect to find 7.5 species present in each of our quadrats.

Cover and frequency values are easiest to understand when the values for the contaminated plots are compared to those of the control. If a contaminated site cover value is 64% and its control is 128%, we can say that the plants in the former have only recovered to half their original status.

The depth of the active layer overlaying the permafrost was also measured in 1980 using graduated metal probes.

Data are presented to allow comparisons between sites and types of spill, as well as to compare the effects up to 1975 with those found in 1980.

4. RESULTS AND DISCUSSION

4.1. EFFECTS OF 1972-1976 OIL SPILLS ON MACKENZIE VALLEY BLACK SPRUCE TAIGA

4.1.1. Norman Wells Burnt Forest Sites

4.1.1.1. Crude Oil Spills

2

4.1.1.1.1. Even 9.1 litre/m Spill

The effects on plant cover and frequency of occurrence of the species of the 1972 crude oil spill at the burnt forest site are given in Tables 2 and 3. The sites look somewhat different from the last recording, in 1975, due to the recovery of a few species (Plate 1). However, percentage plant cover for all species combined remained low at 64% in the spill area compared to 392% in the control i.e. the cover in the spill site is still only 16% of that of the control (Fig. 1a). Overall, 9 species were responsible for the 64% cover value in the contaminated site while 17 species contributed to the high cover of the control. The recovery is notably gradual; 10% was the recorded plant cover in 1974, 20% in 1975, and now 64%, 5 years later. Our estimate of 10 years for re-development of a full plant cover, made in 1975, has not been met. Recovery has been slower than predicted.

Most of the recovery is due to the regeneration of the meadow-horsetail, Equisetum pratense, which comprised 28% of the cover of the site. This 28% cover represents two times that of the control (Table 2) and indicates that the recovery is quite vigorous. This is of special interest because until 1980 no recovery of the horsetail had been recorded and it was thought that the plants had been killed by the oil. It is now apparent that E. pratense can survive for a number of years as underground rhizomes without having above-ground shoots for photosynthesis each year.

Other species which were found near the centre of the 10m x 10m plot and survived the spill or have regenerated include: dwarf horsetail, dwarf birch, shrubby cinquefoil, and labrador tea. Two small black spruce also survived the spill even though all others gradually died out over the initial four post-spill years. The two survivors occur on a raised area in which the oil had killed all the lichens and mosses. It seems probable that the oil did not penetrate to the root system at this point. Recovery also takes the form of invasion of species from the undamaged vegetation growing at the edges of the oiled plots. The three species which were especially good at invasion are alpine bearberry, Bebb's willow, and another willow, Salix myrtillofolia.

A careful search for seedlings revealed almost none. Those which had been found in 1975 had apparently died. The soil surface and its organic mat in the spill site still smelled of crude oil as one walked on it. The taiga sites were very dry and the oil may have aggravated the drought conditions by providing a barrier to downward drainage. Thus, it could be a combination of drought and persistence of toxic oil components which prevented seedling establishment.

Although recovery of some species occurred, the devastation produced by the oil spill is evident 9 years later. Many species present in the control were not found in the spill plots. Most species which were found in 1980 had

not recovered to 100% cover nor to the frequency of the controls (Tables 2 and 3).

4.1.1.1.2. 8500 litre Point Spill (50 barrel)

The damage to vegetation at the 8500 litre point spill had increased in extent from 1975 to 1980. In 1975 an area of 200-300m² was affected (Hutchinson and Hellebust, 1978). Topography had played a key role in determining flow patterns and drainage so that islands of raised vegetation, including lichens, such as Cladina alpestris, had survived. Many of these survivors were dead in 1980. The dead black spruce extended a few metres beyond the zone of dead ground flora. Clearly, the oil had spread underground and affected vegetation not directly contacted during the spill. An oil film had appeared on a pool about 50m downslope from the original spill; the vegetation around the pool is now dead. However, in the central zone of the spill a few vigorous individuals of the cotton-grass Eriophorum scheuchzeri, a sedge, and both species of horsetails were found. The bryophytes seemed, as elsewhere, especially susceptible to oil toxicity.

4.1.1.2. Diesel Oil Spill

The diesel spill at the burned forest site had reduced total cover to 22% by the first post-spill season from 208% before the spill. By 1980, the 4th post-spill summer, cover had increased to 40% (Fig.1). This is somewhat higher than the 6th post-spill summer (1975) recovery in the crude oil site in which percentage cover was 10% in 1975. Interestingly, the contributors to the cover values differ between the sites of the two oil types. Unlike at the crude oil site, the moss Tomenthypnum nitens survived and contributed 18% of the 40% total cover, the trees black spruce and tamarack contribute another 10% and the willows the remaining 12%. The horsetails did not contribute greatly to the recovery of the diesel site as they had at the crude oil site (Tables 2 and 3).

These data strongly suggest that the effects of diesel and crude oil on taiga are somewhat different at the species level. The more volatile arctic diesel might be expected to cause initial severe contact herbicidal damage but then to volatilize more completely, causing less residual toxicity. This is partly borne out by the better performance of species such as black spruce in the diesel site. The reasons for poor horsetail recovery in the diesel site are not at all clear. One possibility is that the diesel oil penetrated the soil better than did the crude oil and thus killed the underground rhizomes of the horsetails.

An effect of oil contamination noted in both types of spills was a decrease in species diversity as indicated by the decrease in the number of species contributing to percentage frequency. In the control plots 34 species contributed to the 882% frequency of species (Table 3); in the diesel and crude oil spill sites the number of species were reduced to 11 and 14, respectively.

4.1.1.3. Effect of Fertilizer Applications to Oil Spill Sites

Fertilizer applications made in 1973 to the crude oil site in the burnt forest had no apparent beneficial effect on vigor, rate of recovery, or species richness. This was a once-only application and it can be argued that it was made at a stage in recovery (2nd post-spill year) when few plants were around to benefit from it.

4.1.2. Norman Wells Mature Forest Sites

4.1.2.1. Crude Oil Spills

4.1.2.1.1. Summer Spills

At the unburned mature forest site at Norman Wells the degree of recovery following summer spills was a good deal less than expected. Total vegetative cover was only 44% at the contaminated site as compared with 296% at the control site (Fig. 1b). The largest contribution to cover was by labrador tea with a cover of 26% (Table 4). Shrub alder was present but the leaves were chlorotic. Chlorosis seems to be a common physiological disorder following both winter and summer spills. A number of rose bushes had apparently survived the summer spill and produced new shoots from below-ground root systems. Similarly, the two pyrolas, P. secunda and P. asarifolia, survived from underground bulbs and rhizomes. Much of the ground cover had originally been composed of one of the feather mosses, Hylocomium splendens. Living shoots of the mosses were found in 1980 after the total devastation caused by the 1972 spill. These seemed to be growing in a number of separate areas and were spreading like a mosaic. It is likely that some shoots or dormant buds actually survived the initial oiling and from these green shoots of feather moss are regrowing from old, dead oiled moss clumps. This moss is abundant in the mature taiga as part of the more shaded ground flora but is adversely affected by fire and by the openness created in a post-fire area.

As in the burnt forest site, there was no survival or regeneration of black spruce or tamarack at the mature forest site. These trees are obviously poor in their ability to recover in the long term from oil spills.

The oil spills not only reduced cover but also species richness. In the control site 24 different species were found in the 50 random quadrats, while only 17 of these occurred in the summer spill site (Table 5). Although all of the missing species were bryophytes, the feather moss, Hylocomium splendens, was the most commonly encountered species with a frequency of 40%. Labrador tea and dwarf horsetail also contributed significantly to total frequency with values of 34% and 24%, respectively.

4.1.2.1.2. Winter Spills

The recovery of the winter spill sites in the mature forest site was substantially greater than at the summer spill site (Plates 3 and 4). This has been the case since the first summer after the March 1973 spill (Figs. 1 and 2). Much of the recovery is due to the production of new shoots by the dwarf shrubs, alpine bearberry and labrador tea, especially the latter. From patches which had been protected behind trees when the oil spraying took place (shadows), mountain cranberry and feather moss were now spreading in 1980.

The recovery of vegetation was favored by the low intensity spraying regime of 6.0 litres/m² in the winter spill site. Vegetative cover for plots sprayed at low intensity reached 142% by 1980 whereas in the 9.1 litre/m² spray treatment cover was only 72% (Fig. 1). In both cases major contributors to cover were green alder and labrador tea; minor contributions were from mountain cranberry, dwarf birch, dwarf horsetail, bearberry and woodgrass. In the low intensity spray plot, the feather moss Hylocomium splendens showed significant recovery by 1980 (22% cover) as it had in the summer spill sites (Table 4).

Recovery of abundance of species, measured by total frequency percentages, had not changed since 1975 (Fig. 2). However, a notable finding was that the lichens and mosses were reoccurring in the quadrats albeit at a low individual frequency (Table 5). This is a significant change from previous observations at the mature forest site.

Although 9 years is sufficient for some recovery of vegetation after an oil spill, it is still not enough time to raise cover and frequency values of a winter oil spill site to pre-spill levels. Vegetation contaminated by summer spills would be expected to take much longer to recover.

4.2 EFFECTS OF THE 1972-1975 CRUDE OIL SPILLS ON LOW ARTIC TUNDRA AT TUKTOYAKTUK

4.2.1. Cotton-grass Tundra

The recovery from the effects of summer and winter spills are illustrated in Plates 5-8 and cover and frequency values for species are given in Table 6. Total vegetation ground cover and frequency from 1972 to 1980 are shown in Figures 3 and 4.

4.2.1.1. Summer Spill : Effects on both fertilized and unfertilized quadrats.

At the summer spill site 2/5 of the plot was fertilized in 1973 and the remaining 3/5 was left unfertilized. Thus, the overall cover value of 126% combines the 96% cover of the fertilized portion and 175% cover of the unfertilized area in the proportions of 2/5 and 3/5, respectively. The total cover value of the control plot, 342% (Fig. 3b), which was also partially fertilized, was derived in the same manner. Therefore, the recovery in plant cover in the spill plot in 1980 is only 36.8% of that of the control, with about twice as much contribution to regrowth from the fertilized areas as from the unfertilized area. Growth of the cotton-grass Eriophorum vaginatum was especially stimulated by the application of ammonium nitrate fertilizer and much of it had flowered in 1980 in the oiled plots. Another cotton-grass species, E. angustifolium, had invaded both the summer and winter spill plots (Table 6). This species is typical of wetter sites, often with standing water.

The frequency values given in Tables 7 and 8 illustrate that little invasion or expansion of species had taken place at the spill site since 1974 though cover values of those species which survived continued to improve. For example: the total frequency only increased to 358% in 1980 from 306% in August 1973 (Fig. 4b); whereas the total cover value increased from 47% to 126% (Fig 3b). Much of the increase in cover is due to the revegetation by cotton-grass, E. vaginatum. The number of species occurring on average per

plot substantiates this lack of invasion by new species. Thirty-one species were recorded in the control plot whereas only 15 were recorded in the contaminated plot. As in the taiga sites, many mosses and lichens were killed by the spill and are unable to recover rapidly or re-invade. These species occur principally in the hollows between the cotton-grass tussocks where oil accumulated most. Either these areas still have toxic concentrations of oil or the propagules necessary for recolonization are not readily available. The moss which was the exception to the rule is Polytrichum juniperum. It plays a similar role to that of the feather moss Hylocomium splendens at Norman Wells. Unlike at Norman Wells, some lichens such as Cetraria cuculata and C. islandica showed signs of regeneration for the first time in 1980.

4.2.1.2. Winter Spill

At the winter spill sites in Tuktoyaktuk the vegetation looked very healthy, with the tall, dark green cotton-grass E. vaginatum dominating (Plates 6 and 7). The overall cover was 284% with 260% of this contributed by the cotton-grass (Table 6). Only 5 other species contributed to cover. Recovery was much greater, therefore, in the winter spill site than the summer spill sites. Overall cover in the unfertilized area of the summer spill site was 96%. Interestingly, the cotton-grass of the winter spill site had not flowered; whereas in the summer spill site, though with low cover value, it had flowered.

4.2.2. Dwarf Shrub - Lupine Tundra

By 1980 the effects of the summer crude oil spill onto the dwarf shrub-lupine tundra were similar to those on the cotton-grass tundra. In the two sites the percentage of cover was similar though the species contributing to it were different (Table 8 and Fig. 3a). The main contributors to the cover of the shrub-lupine site were birch (50%) and the arctic willow Salix glauca (58%). These shrubs have been the main survivors since 1973 and play the equivalent role to that of the cotton-grass which dominated recovery in the other tundra site. It has taken 8 growing seasons to double the post-spill cover values; cover had reached 114% by 1980 from 56% in 1973 (Fig. 3a). This still represents only about 1/3 recovery of vegetation after the spill; cover of the control plot was 290%.

As with other spill sites, the number of species per site decreased following the spill (Table 7). Only 11 species, 1 of which was a bryophyte, contributed to the overall frequency of 270% (Fig. 4a), whereas in the control 31 species contributed to frequency, 17 of which were lichens and bryophytes. A new species which invaded the spill plot was the 'weedy' reed-bent grass Calamagrostis canadensis. This genus seems to have the ability to invade the contaminated sites. Another closely related species C. purpurascens was noted to invade the Norman Wells sites and C. canadensis spread in the cotton-grass site at Tuktoyaktuk. Though the latter species is a frequent member of the tundra associations it apparently can exploit disturbances and stresses of various kinds e.g. fire, pipeline and highway construction, seismic line activity, etc.

4.3. EFFECTS OF SPILLS ON THE DEPTH OF THE ACTIVE LAYER

It should be recalled that apart from the first year of the spills, rather insignificant differences had been found in depth of active layer between oiled and control sites. The effect of trampling during recording of data was to increase the depth of the thaw each summer.

At Norman Wells, in the burnt forest site, the depth of the active layer in 1980 was greatest in the diesel spill site (85.3 cm), less in the crude spill site (73.6 cm) and least in the control site (50.3 cm) (Table 9). The large increase in thaw layer in the diesel site is probably due to the more severe effect of the diesel compared to the crude oil on the ground flora and the spruce trees such that heat input to the soil is increased. The dark brown ground layer undoubtedly will absorb more radiation than the green, vegetated areas, since albedo is decreased.

In the mature forest site at Norman Wells, the spills significantly increased the active depth layer, though not as much as in the burnt forest site (Table 9). Again, this probably relates to the higher heat input in the more exposed, burnt forest site where trees are smaller and more light reaches the ground.

The increases in the depth of thaw in the oiled plots at the spruce forest sites were unexpected and suggest that we need to keep on monitoring the sites to see if increased depths of thaw might develop over a number of years, or may be dependent upon a particularly warm summer for development. Since the spills used in these studies were of very low intensity compared with accidental spillages it seems reasonable to expect substantial thermokarst to accompany a spill.

At Tuktoyaktuk the only differences on the active thaw layer were those between the hummocks and hollows at each site; the hummocks had consistently deeper active thaw layers.

5. SOME RECENT FINDINGS FROM ALASKAN OIL FIELD STUDIES

Since the 1975 report for DINA (Hutchinson and Hellebust, 1978) a number of new Alaskan studies have been reported. Many of the findings are confirmatory to those reported here or in previous reports. This certainly suggests that many generalizations may be developed with respect to effects of oil spills on terrestrial arctic ecosystems, and on patterns of recovery and species sensitivity. A number of the key findings are listed.

Johnson et al (1980) confirmed our earlier findings that death of black spruce (Picea mariana) after an oil spill may take as long as 2 years to occur. They also recommend serious consideration of a 'no clean-up' strategy after an oil spill as the most likely to lead to rapid recovery. They noted the main oil spill effects to be caused by its contact herbicidal action. Lichens and mosses suffered particularly heavy mortality in their spills near Fairbanks, Alaska. This repeats the Canadian experience.

Jenkins et al (1978) noted that black spruce had some of the most delayed damage of any species. Cumulative injuries were also largely limited to evergreen species. During the second growing season, increasing amounts of black spruce foliage became chlorotic, turned brown and fell off. They also noted more damage from a summer than a winter spill in spruce taiga. Again, the similarities to our earlier findings are striking.

Several authors have now reported on the tolerance of the cotton-grass, Eriophorum vaginatum, to oil spills, and its ability to recover afterwards (e.g. Jenkins et al, 1978; Johnson et al, 1980). The latter attribute this ability to its relatively deeper root system and the tendency of the tussocks to stick up above the surrounding vegetation and soil where oil accumulates. Chapin III and Chapin (1980) also noted the excellent ability of E. vaginatum to revegetate disturbed areas using transplants. They also noted its highly favourable response to both high nitrogen and high phosphorous fertilizer treatments. The grass Calamagrostis canadensis was noted as a native weedy species also capable of re-vegetating disturbed areas. Everett (1978) confirms the remarkable tolerance of the moss Polytrichum juniperum to oil spills.

Walker et al (1978) noted that cotton-grass and willows showed substantial recovery from crude oil spills made at 12 litre/m² onto tundra at Prudhoe Bay. The wetter the site at the time of the spill, the better the recovery. Dryas integrifolia on dry sites was killed. They noted that in identical experiments using diesel instead of crude oil all species except an aquatic moss were killed. This appears to parallel in many ways our findings for the Canadian arctic and sub-arctic.

One point of difference was that Johnson et al (1980) reported that no regrowth had been seen on any species which lost its foliage as a result of oil damage. This is contrary to our tundra and taiga experiments (Hutchinson et al, 1974), and with that of Wein and Bliss (1973).

McKendrick and Mitchell (1978a) examined the effects of fertilizing and seeding oil-damaged arctic tundra on vegetational recovery at Prudhoe Bay. Their studies were made over 6 growing seasons. Damage to the mosses persisted throughout the study period in lightly oiled areas. Nitrogen fertilizer failed to speed up recovery (cf our findings) while phosphorous had a beneficial effect. These results will surely be dependent upon the species being consi-

dered and on the original nutrient status of the site.

McKendrick and Mitchell (1978b) also examined the effects of burning spilled oil on rates of vegetation recovery. They found that burning during the summer was much more detrimental to plant survival than winter burning. Significant amounts of dormant and near dormant vegetation survived hot burns in September when the soil was frozen to a depth of at least 4 cms. In summer, delaying burning by either 48 hours or one month after spilling significantly decreased plant survival. Woody species apparently survived burning and oiling and regrew from stump shoots.

The greatest increase in depth of active layer thaw was in areas where the surface was blackened by the spilled oil. Oil tended to decompose very slowly in wet soils and at depth (Johnson et al, 1980). From a point spill of hot oil, spruce died sequentially downslope from the spill point, with needles turning chlorotic and falling off prematurely. They noted the winter kill factor as an important one, as we had at Norman Wells (Hutchinson and Hellebust, 1973; Hutchinson et al, 1974; Hutchinson and Freedman, 1978).

It is in many ways re-assuring to find that the recent intensive Alaskan studies are reporting similar or identical findings to those from our black spruce taiga and tundra spills. The common responses include the delayed death of black spruce, the ability of certain species to recover, and the ability of cotton grass to respond vigorously to fertilizer applications. This substantially increases our confidence in the statement that across extensive arctic and sub-arctic areas the responses of vegetation are fairly predictable.

6. REFERENCES

- Chapin 111, F.S. and M.C. Chapin (1980). Revegetation of an arctic disturbed site by native tundra species. *J.Appl.Ecol.* 17:449-456.
- Everett, K.R. (1978). Some effects of oil on the physical and chemical characteristics of wet tundra soil. *Arctic* 31(3):260-276.
- Freedman, B. and T.C. Hutchinson (1976). Physical and biological effects of experimental crude oil spills on low arctic tundra in the vicinity of Tuktoyaktuk, N.W.T., Canada. *Can. J. Bot.* 54:2219-2230.
- Hutchinson, T.C., and B. Freedman, (1975). The impact of crude oil spills on arctic and sub-arctic vegetation. *Proc. Circumpolar Conference on Northern Ecology*. NRC Ottawa 1. 175-182.
- Ibid. (1978). The effects of crude oil and diesel oil spills on sub-arctic vegetation near Norman Wells, N.T.W. *Can.J.Bot.* 56:2424-2433.
- Hutchinson, T.C., and J.A. Hellebust (1973). Oil spills and vegetation at Norman Wells, N.W.T. Environmental Social Committee, Northern Pipelines, Task Force on Northern Oil Development. Information Canada.
- Ibid (1978). Vegetational recovery in the Canadian arctic after crude and diesel oil spills. Pub. Environment Division, Northern Natural Resources and Environment Branch, Dept. Indian Affairs and Northern Development. ALUR 75-76-83. 62pp.
- Hutchinson, T.C., J.A. Hellebust, and M. Telford (1974). Oil spill effects on vegetation and soil microfauna at Norman Wells and Tuktoyaktuk, N.W.T., Report to DINA. Environmental- Social Program, Northern Pipelines 74-14. Information Canada. Cat. No. R57-10/ 1974, 111pp.
- Ibid. (1975). Oil spill effects on vegetation and soil microfauna at Norman Wells and Tuktoyaktuk, N.W.T., Report to DINA. Environmental Social Program, Northern Pipelines. 75-14. Information Canada, ALUR. 74-75-83. 142pp.
- Jenkins, T.F., L.A. Johnson, C.M. Collins, and T.T. McFadden (1978) The physical and chemical and biological effects of crude oil spills on black spruce forest, Interior Alaska. *Arctic* 31(3):305-323.
- Johnson, L.A., E.B. Sparrow, T.F. Jenkins, C.M. Collins, C.V. Davenport, and T.T. McFadden (1980). The fate and effects of crude oil spilled on sub-arctic permafrost terrain in Interior Alaska. Corvallis Environmental Res. Lab. Office Res. and Develop. U.S. EPA, EPA-600/3 - 80-040. 126pp.
- Mackay, D., C.R. Phillips and M.E. Charles (1974). Crude oil spills on northern terrain. Environmental Society Committee, Northern Pipelines, Task Force on Northern Oil Development. Information Canada, Ottawa.

McKendrik, J.D., and W.W. Mitchell (1978a). Fertilizing and seeding oil-damaged arctic tundra to effect vegetation recovery at Prudhoe Bay, Alaska. *Arctic* 31(3):296-304.

Ibid. (1978b). Effects of burning crude oil spilled on to six habitat types in Alaska. *Arctic* 31(3):277-295.

Walker, D.A., P.J. Webber, K.R. Everett, and J. Brown (1978). Effects of crude oil and diesel oil spills on plant communities at Prudhoe Bay , Alaska, and the derivation of oil spill sensitivity maps. *Arctic* 31(3):242-259.

Wein, R.S., and L.C. Bliss (1973). Experimental crude oil spills on Arctic plant communities. *J. Appl. Ecol.* 10: 671-682.

Table 1. Summary of oil spill type, location and date of spill. See text for details.

<u>SITE</u>	<u>COMMUNITY TYPE</u>	<u>TYPE OF OIL</u>	<u>TIME OF YEAR/DATE</u>	<u>METHOD</u>
1. Norman Wells	Burnt forest - taiga	crude	summer - June 1972	even 9.1 litre/m ²
2. Norman Wells	Mature black spruce forest - taiga	crude	summer - June 1972	"
3. Tuktoyaktuk	Cotton-grass - tundra	crude	summer - July 1973	"
4. Tuktoyaktuk	Dwarf shrub-lupine - tundra	crude	summer - July 1973	"
5. Cape Parry*	<u>Dryas</u> - xeric tundra	crude	summer - August 1974	"
6. Norman Wells	Mature black spruce forest - taiga	crude	winter - March 1973	"
7. Norman Wells	Mature black spruce forest - taiga	crude	winter - March 1973	even 6.0 litre/m ²
8. Tuktoyaktuk	Cotton-grass - tundra	crude	winter - Feb. 1974	even 9.1 litre/m ²
9. Norman Well	Burnt forest - taiga	diesel	summer - June 1975	"
10. Norman Wells	Burnt forest - taiga	crude	summer - 1973	8500 litre point spill
11. Norman Wells	Burnt forest - taiga	crude	summer - August 1973	fertilizer treatment
12. Tuktoyaktuk	Cotton-grass - tundra	crude	summer - August 1973	fertilizer treatment

*not monitored in 1980.

Table 2. Percentage cover data for all species recorded in the burnt forest site at Norman Wells, 1980, after spills of crude or diesel oil. Theoretically, if plots were unaffected by oil the cover values of the spill sites, as % of control, would all be 100. The symbol + indicates that the species was present in the plots but not significant in terms of cover.

Species	Cover value in control plot, 1980 (percentage)	Cover values in spill sites as % of control plots, 1980.	
		Summer Diesel	Summer Crude
<u>LICHENS</u>	+		
<u>MOSSES/BRYOPHYTES</u>			
Equisetum pratense	14	0	200
Tomenthypnum nitens	48	38	8
Others	40	0	15
<u>TREES</u>			
Larix laricina	28	7	0
Picea mariana	152	5	0
<u>SHRUBS</u>			
Betula glandulosa	22	0	36
Potentilla fruticosa	18	0	0
Salix arbusculoides	4	200	100
S. myrtillofolia	32	13	25
Others	2	0	0
<u>SEDGES/GRASSES</u>			
Calamagrostis spp.	+		
Carex podocarpa	12	0	50
C. scirpoidea	2	0	0
Others	+		
<u>HERBS</u>			
Arctostaphylus rubra	16	0	0
Others	2	0	0
Total % cover of all species	392		

Table 3. Percentage frequency data for all species recorded in the burnt forest site at Norman Wells, 1980, after spills of crude or diesel oil. Theoretically, if plots were unaffected by oil the '% of control' values would all be 100.

Species	Frequency value in control plot, 1980 (percentage)	Frequency value in spill site as % of control plot	
		Summer Diesel (1975)	Summer Crude (1972)
<u>LICHENS</u>	92	0	0
<u>MOSSES/BRYOPHYTES</u>			
Equisetum pratense	80	20	120
E. scorpioides	88	0	23
Ptilidium ciliare	4	0	600
Tomenthypnum nitens	64	63	13
Others	34	0	24
<u>TREES</u>			
Larix laricina	16	25	0
Picea mariana	60	20	7
<u>SEDGES/GRASSES</u>			
Calamagrostis spp.	12	34	0
Carex podocarpa	60	7	47
C. scirpoidea	8	0	0
Others	12	0	0
<u>SHRUBS</u>			
Betula glandulosa	24	0	67
Potentilla fruticosa	52	0	15
Salix arbusculoides	0	8*	16*
S. myrtillofolia	40	10	30
Others	56	50	7
<u>HERBS</u>			
Arctostaphylos rubra	72	6	0
Others	108	4	0
Total % frequency of all species	882		

* spill values calculated assuming a control value of 1

Table 4. Percentage cover for species in the mature forest site at Norman Wells, 1980. Data for crude oil summer and winter spills.

Species	Summer	Winter	
		6.0 l/m ²	9.1 l/m ²
<u>MOSSES/HORSETAILS</u>			
Dicranum bojeani	0	0	0
Equisetum scorpioides	2	10	22
Hylocomium splendens	6	22	0
Tomenthypnum nitens	0	0	4
<u>TREES</u>			
Larix laricina	0	0	4
Picea mariana	0	4	4
<u>GRASSES</u>			
Oryzopsis sp.	4	10	2
<u>SHRUBS/HERBS</u>			
Alnus crispa	2	54	0
Arctostaphylus rubra	0	2	10
Betula glandulosa	0	4	0
Ledum palustre var. groenlandicum	26	28	12
Potentilla fruticosa	0	0	6
Rosa acicularis	2	0	0
Salix bebbiana	2	0	0
S. myrtillofolia	0	2	0
Vaccinium vitis-idaea	0	6	6
Total % cover for all species	44	142	70

Table 5. Percentage frequency for species in the mature forest site at Norman Wells, 1980. Data for crude oil summer and winter spills.

Species	Summer	Winter	
		6.0 l/m ²	9.1 l/m ²
<u>LICHENS</u>			
Alectoria jubatum	6	8	2
Cetraria lilesii	2	6	0
Cladonia alpestris	10	0	0
Parmelia fraudans	2	0	0
Peltigera canina	2	0	0
<u>MOSESSES/BRYOPHYTES</u>			
Aulacomnium acuminatum	2	0	0
Dicranum bojeani	0	2	2
Equisetum scirpoides	24	42	42
Hylocomium splendens	40	34	12
Mnium sp.	0	4	0
Ptilidium ciliare	0	2	0
Tomenthypnum nitens	0	4	18
<u>TREES</u>			
Larix laricina	0	0	6
Picea mariana	0	16	10
<u>SEDGES/GRASSES</u>			
Carex scirpoidea	0	4	4
Carex sp.	0	2	6
Oryzopsis sp.	8	16	16
<u>SHRUBS/HERBS</u>			
Alnus crispa	12	64	10
Arctostaphylus rubra	2	10	18
Betula glandulosa	4	2	10
Ledum palustre var. groenlandicum	34	38	28
Potentilla fruticosa	0	2	6
Pyrola asarifolia	0	8	0
P. secunda	2	2	0
Rosa acicularis	2	2	2
Salix bebbiana	6	8	4
S. myrtillofolia	0	2	0
Vaccinium vitis-idaea	8	44	34
Total % frequency of all species	166	322	230

Table 6. Percentage cover and frequency of species recorded in the cotton-grass site at Tuktoyaktuk following a summer crude oil spill (1973) and a winter crude oil spill (Feb. 1974).

Species	Cover		Frequency	
	Summer	Winter	Summer	Winter
<u>LICHENS</u>				
<i>Cetraria cuculata</i>	0	0	48	0
<i>C. islandica</i>	0	0	12	4
<i>Cladonia cornuta</i>	0	0	2	2
<i>Dactylina arctica</i>	0	0	2	0
<u>MOSESSES/BRYOPHYTES</u>				
<i>Aulacomnium</i> sp.	0	0	0	2
<i>Lepidozia reptans</i>	0	0	2	2
<i>Mnium</i> sp.	0	0	0	18
<i>Polytrichum juniperinum</i>	8	0	52	32
<i>Ptilidium</i> sp.	0	0	0	4
<i>Sphagnum</i> sp.	0	0	0	4
<u>SEDGES/GRASSES</u>				
<i>Calamagrostis canadensis</i>	8	6	28	46
<i>Carex bigelowii</i>	4	0	4	4
<i>Eriophorum angustifolium</i>	6	2	4	6
<i>E. vaginatum</i>	78	260	82	90
<u>SHRUBS/HERBS</u>				
<i>Betula nana</i>	18	6	56	68
<i>Empetrum nigrum</i>	0	0	6	26
<i>Ledum palustre</i> var. <i>decumbens</i>	2	8	22	54
<i>Rubus chamaemorus</i>	0	2	26	82
<i>Salix glauca</i>	0	0	0	2
<i>Vaccinium vitis-idaea</i>	2	0	12	56
Total	126	284	358	502

Table 7. The numbers of different species found in 50 quadrats of 25 x 25 cm in the oiled and control plots at Norman Wells and Tuktoyaktuk in August 1980. These are further sub-divided into lichens and bryophytes (cryptogram) and vascular plants.

Site	No. Species in Plots		
	Total	Cryptogram	Vascular
<u>NORMAN WELLS</u>			
1) Burnt Forest			
Control	34	9	25
Crude oil summer spill	14	4	10
Diesel oil summer spill	11	1	10
2) Mature Forest			
Control	32	14	18
Crude oil summer spill	18	7	11
Crude oil winter spill			
6.0 l/m ²	24	8	16
9.1 l/m ²	19	3	16
<u>TUKTOYAKTUK</u>			
1) Cotton-Grass Tundra			
Control	31	21	10
Crude oil summer spill	15	6	9
Crude oil winter spill	19	9	10
2) Dwarf Shrub-Lupine			
Control	31	17	14
Crude oil summer spill	11	1	10

Table 8. Percentage cover and frequency data for summer oil spill plots and controls on the dwarf shrub-lupine tundra at Tuktoyaktuk. Cover/frequency values of oiled plots given as a % of the control value; thus, a 100% cover/frequency value indicates full recovery.

Species	Control (%)		Spill Sites (% of control)	
	Cover	Frequency	Cover	Frequency
<u>LICHENS</u>				
Alectoria jubatum	0	20	0	0
Cetraria cuculata	0	8	0	0
C. islandica	0	10	0	0
Lepidozia reptans	0	2	0	100
Nephromum arcticum	0	8	0	0
Parmelia physodes	0	48	0	0
Others	0	26	0	0
<u>MOSESSES/BRYOPHYTES</u>				
Aulacomnium acuminatum	0	0	0	0
A. palustre	0	4	0	0
Dicranum sp.	0	4	0	0
Hypnum cupressiforme	0	12	0	25
Mnium sp.	2	22	0	18
Phytidium sp.	0	24	0	0
Thuidium sp.	0	4	0	0
<u>SEDGES/GRASSES</u>				
Calamagrostis canadensis	2	40	300	55
Carex bigelowii	6	18	0	0
Festuca rubra	0	4	0	150
Poa arctica	0	8	0	100
<u>SHRUBS/HERBS</u>				
Arctostaphylos alpina	8	8	0	0
Betula nana	50	92	100	91
Empetrum nigrum	62	88	0	7
Ledum palustre var. decumbens	74	90	16	36
Lupinus arctica	2	30	0	7
Pyrola secunda	2	34	0	6
P. grandiflora	0	0	0	2*
Rubus chamaemorus	0	2	2*	100
Salix glauca	58	84	76	86
Stellaria edwardsii	0	2	0	300
Vaccinium vitis-idaea	24	78	0	21
Total	290	770	39	35

* spill values calculated assuming a control value of 1

Table 9. Mean depth of thaw (active layer) of permafrost in the taiga sites of Norman Wells and the tundra sites at Tuktoyaktuk, following crude oil spills. Data recorded August 4/5, 1980. Mean and standard deviations are given in centimetres.

A) NORMAN WELLS		
	<u>Mature forest</u>	<u>Burned forest</u>
Control	47.4 $\pm$ 9.6*	50.3 $\pm$ 7.0**
Summer Crude	61.1 $\pm$ 11.5	73.6 $\pm$ 11.9
Winter Crude	56.7 $\pm$ 15.6	-
Summer Diesel	-	85.3 $\pm$ 9.7*
Untrampled area	-	70.7 $\pm$ 11.9
B) TUKTOYAKTUK		
	<u>Cotton-grass</u>	<u>Dwarf shrub-lupine</u>
Control		
hummock	42.1 $\pm$ 6.9	52.2 $\pm$ 10.0
hollow	27.5 $\pm$ 3.9*	21.7 $\pm$ 5.9*
Summer Crude		
hummock	38.0 $\pm$ 6.2	53.0 $\pm$ 8.9
hollow	31.1 $\pm$ 6.5*	25.0 $\pm$ 4.8*
Winter Crude		
hummock	48.2 $\pm$ 6.1	-
hollow	33.5 $\pm$ 6.0	-
Untrampled		
hummock	-	41.1 $\pm$ 9.5
hollow	-	22.6 $\pm$ 7.1*

* and ** indicate that values differ significantly from those not so marked ($p < 0.05$) within columns

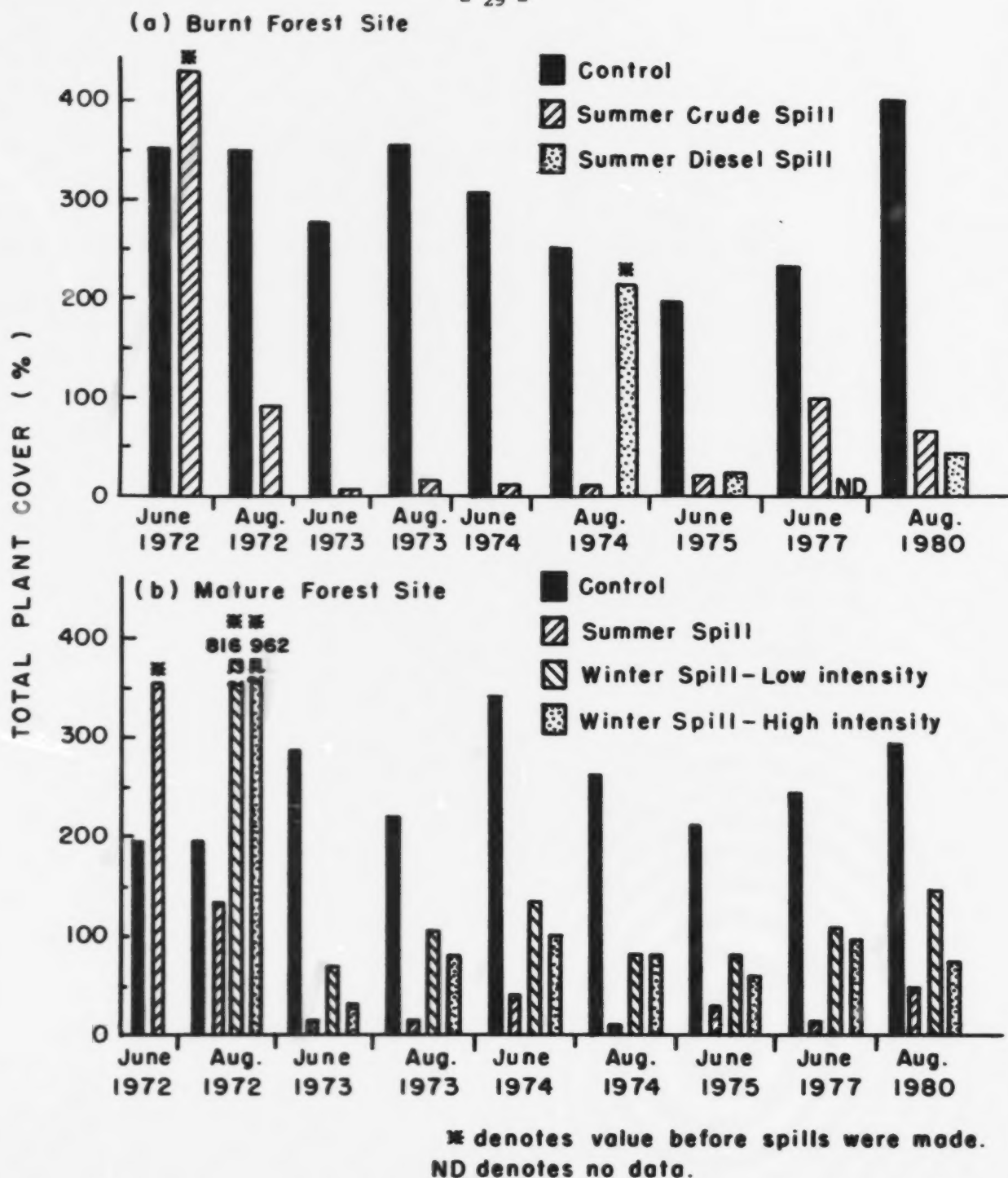


Fig. 1 Total vegetation ground cover (%) at boreal forest sites at Norman Wells following crude oil spills in the summer of 1972 and the winter of 1973; the diesel spill was made in the summer of 1975.

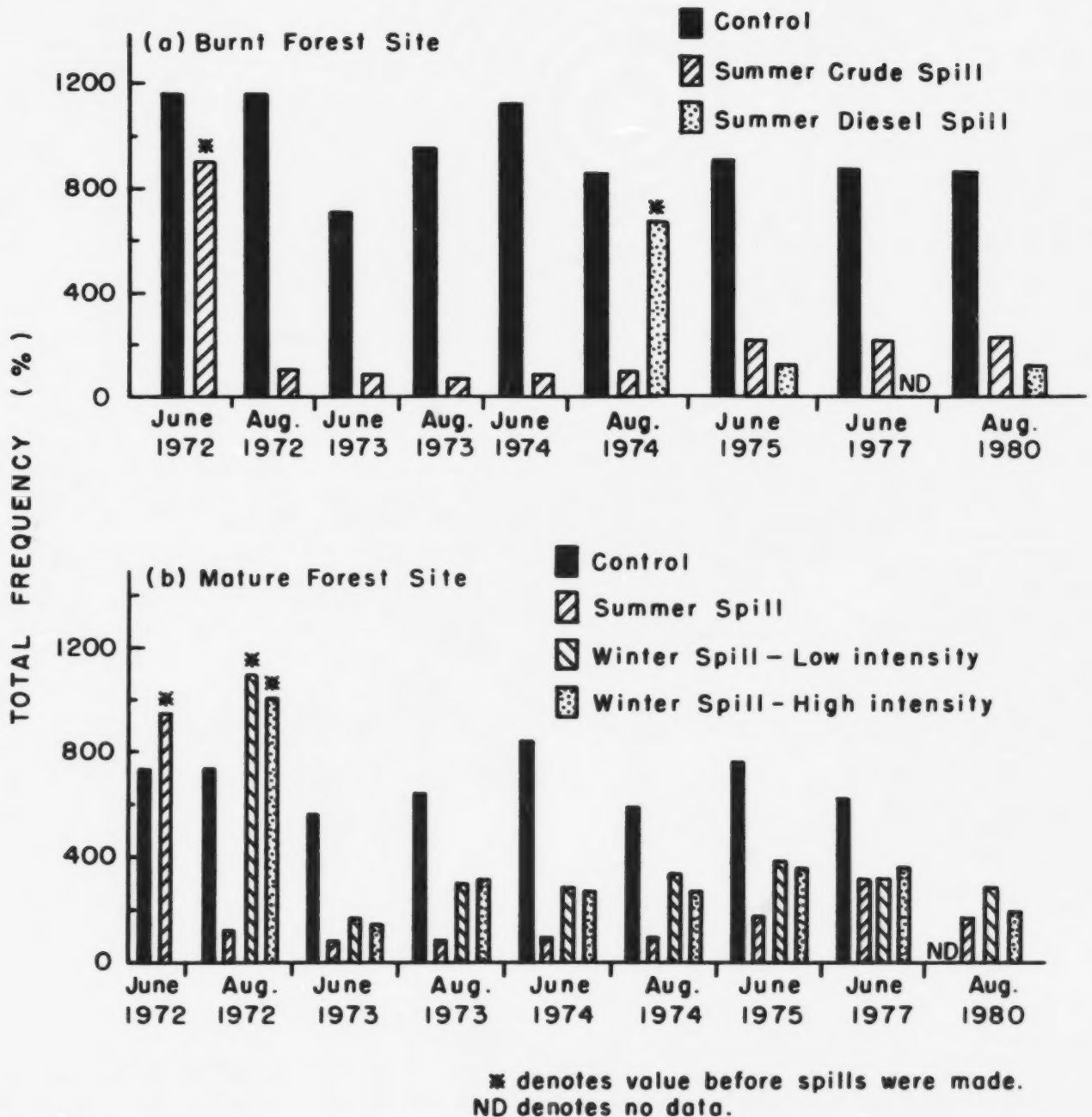


Fig. 2 Total frequency values (summed per species frequency) at boreal forest sites at Norman Wells following crude oil spills in the summer of 1972 and the winter of 1973; the diesel spill was made in the summer of 1975.

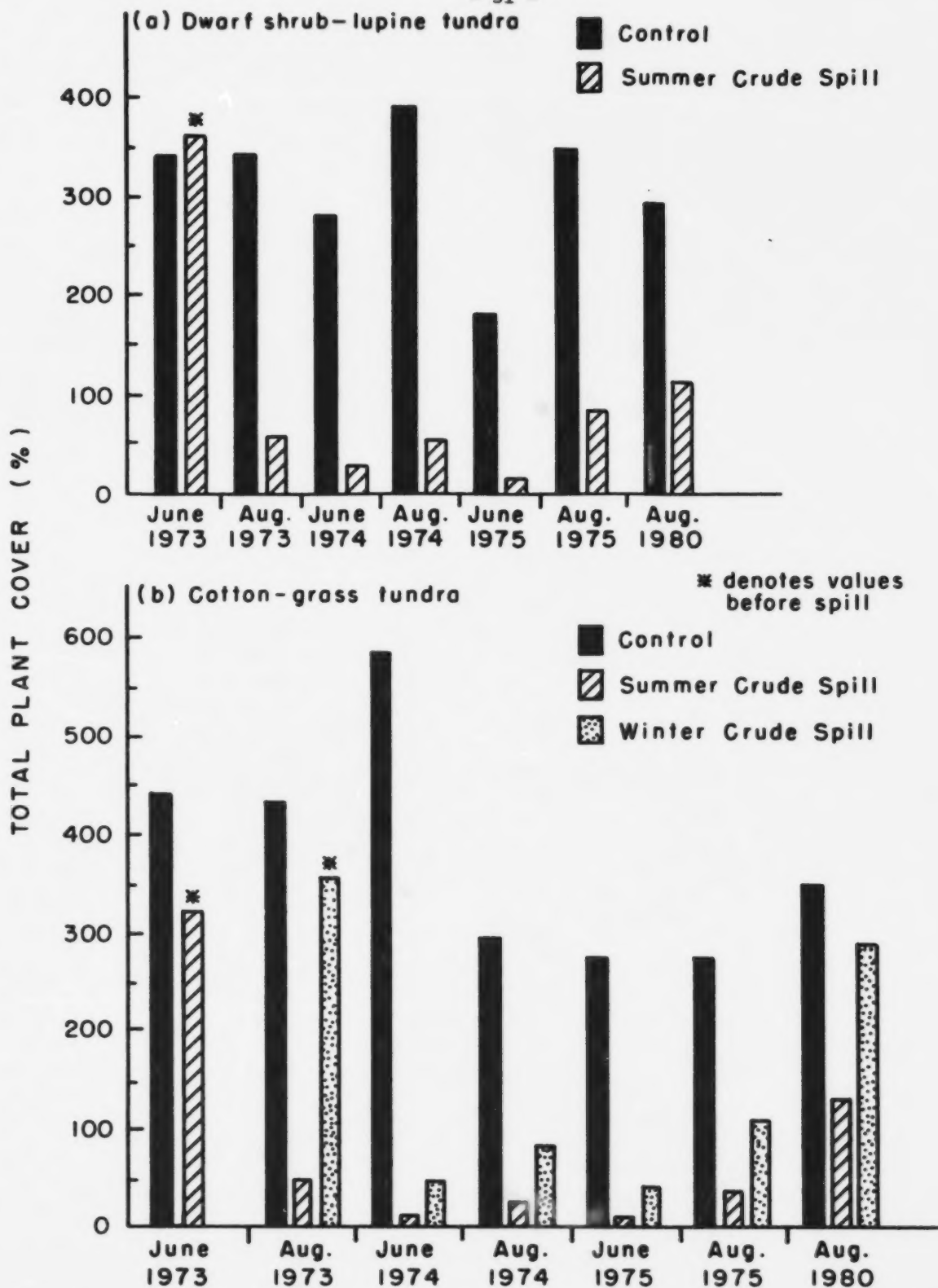


Fig. 3 Total vegetation ground cover (%) at tundra sites at Tuktoyaktuk following crude oil spills in the summer of 1973 and the winter of 1974.

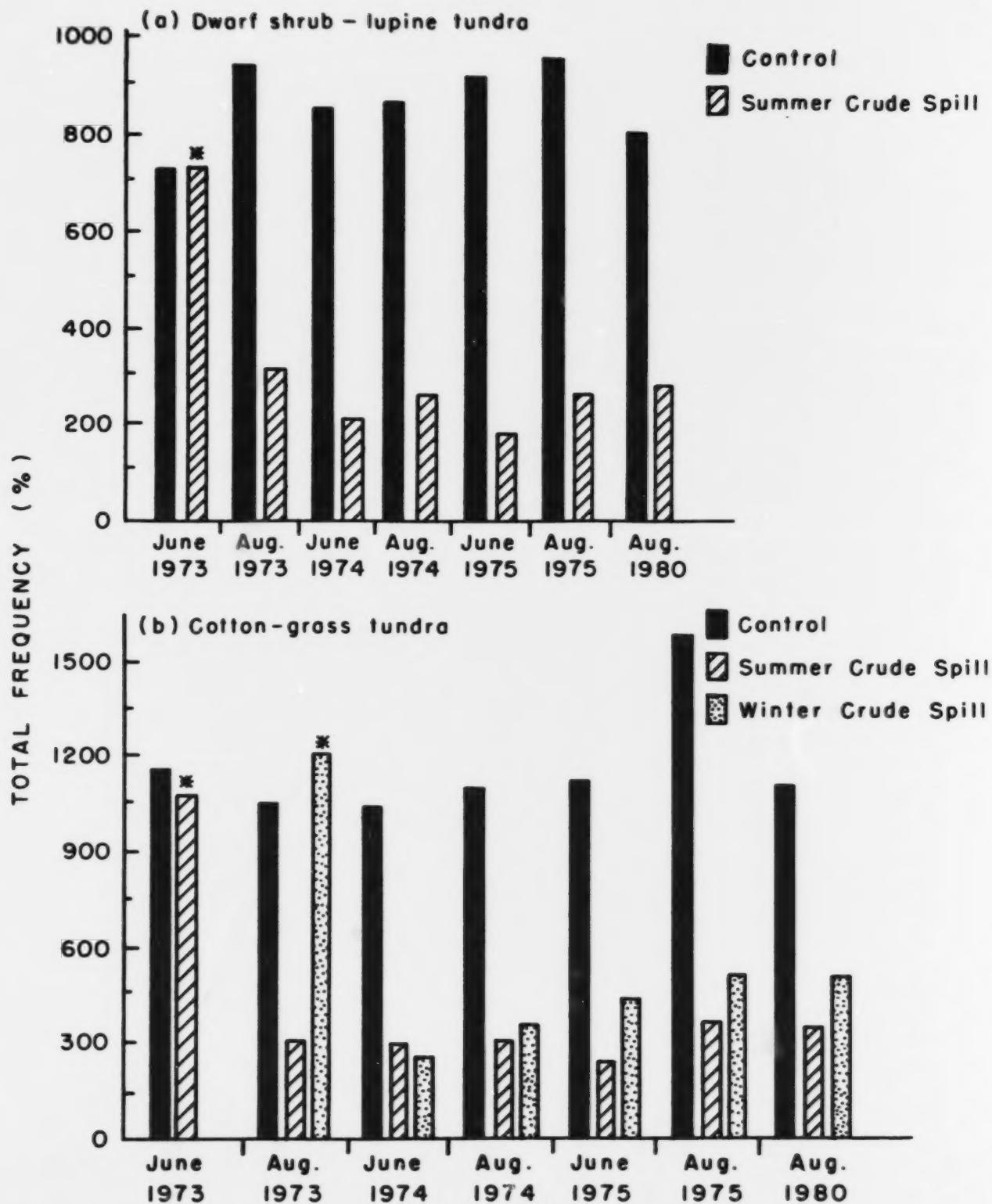


Fig. 4 Total frequency values at tundra sites at Tuktoyaktuk following crude oil spills in the summer of 1973 and the winter of 1974.

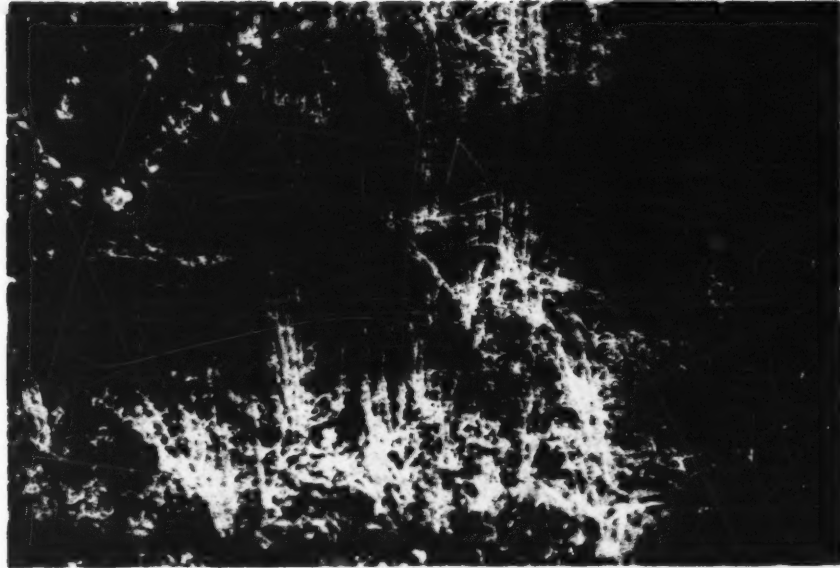


Plate 1. Summer spill of crude oil made onto black spruce taiga in June 1972, photographed August 1980. Note considerable area of ground still bare. The horsetail Equisetum pratense has recovered from its initial defoliation. Dwarf birch Betula glandulosa has also produced vigorous new shoots.



Plate 2. The devastated area created following a spill of Arctic diesel made in June 1975 and photographed in August 1980. Almost all of the ground flora is still dead, as are the black spruce. Norman Wells.

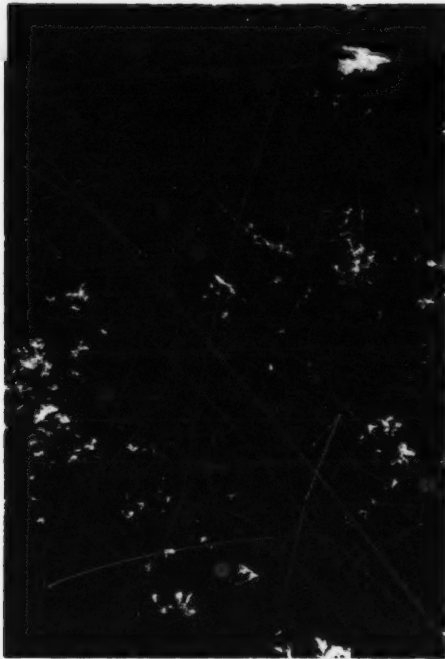


Plate 3. Winter spill site in the taiga at Norman Wells - mature forest. Photograph taken in July 1973, the first summer after the March 1973 spill. The survival of the black spruce and tamarack can be seen. New shoots of alpine bearberry Arctostaphylos rubra can also be seen.



Plate 4. Winter spill site at Norman Wells, oil spilled in 1973, photographed in August 1980. The ground cover has almost reached 100%. Vigorous growth of alpine bearberry and Labrador tea can be seen in the foreground. The shrubs Bebb's willow and green alder are in the background.



Plate 5. Control site in the cotton-grass tundra site at Tuktoyaktuk, photographed in August 1980. Dwarf birch, cloudberry, mountain cranberry and Labrador tea can be seen amongst the cotton-grass Eriophorum vaginatum tussocks.



Plate 6. Winter oil spill plot in cotton-grass tundra at Tuktoyaktuk. Spill made in February 1974 and photographed in August 1980. The especially vigorous growth of the cotton-grass Eriophorum vaginatum can be seen, with dead ground cover creating gaps in areas between tussocks (upper right and left). Cloudberry and dwarf birch also show good recovery.

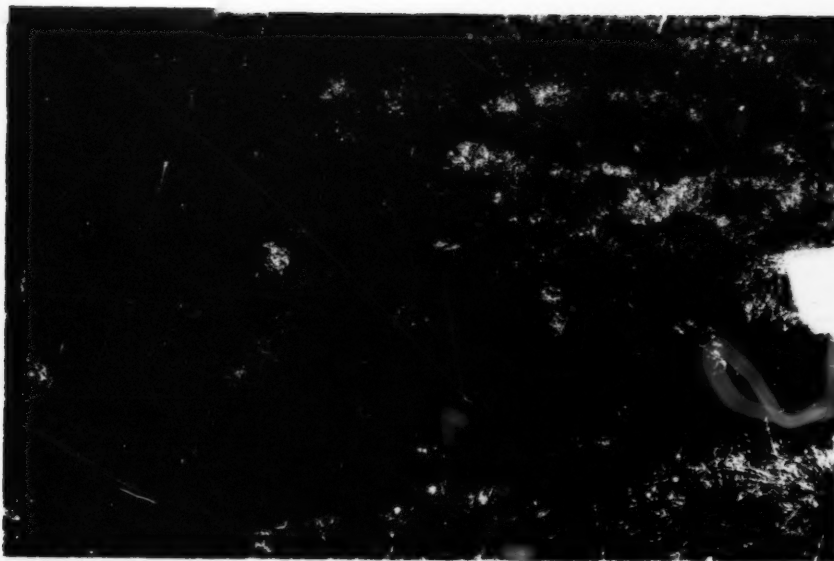


Plate 7. Overview of winter spill site in the cotton-grass tundra at Tuktoyaktuk showing dead areas in hollows between dark green vigorous Eriophorum vaginatum tussocks. Photographed August 1980 after the February 1974 experimental oil spills.



Plate 8. Close-up of summer oil spill site in cotton-grass tundra at Tuktoyaktuk, photographed August 1980 after July 1973 spill. Almost total absence of recovery is seen.

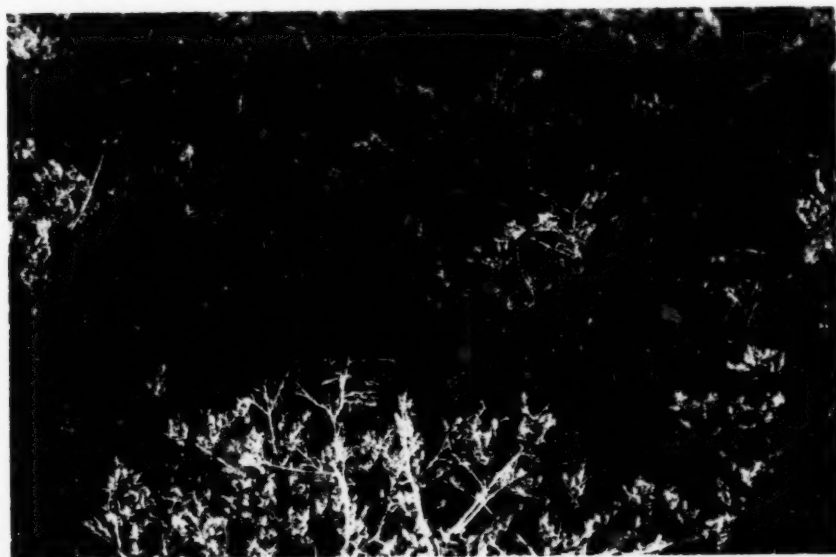


Plate 9. Summer oil spill site in dwarf willow - dwarf birch - lupine tundra at Tuktoyaktuk in June 1975. Spill made in July 1973. Vigorous regrowth of the willow Salix glauca and the dwarf birch Betula nana can be seen.

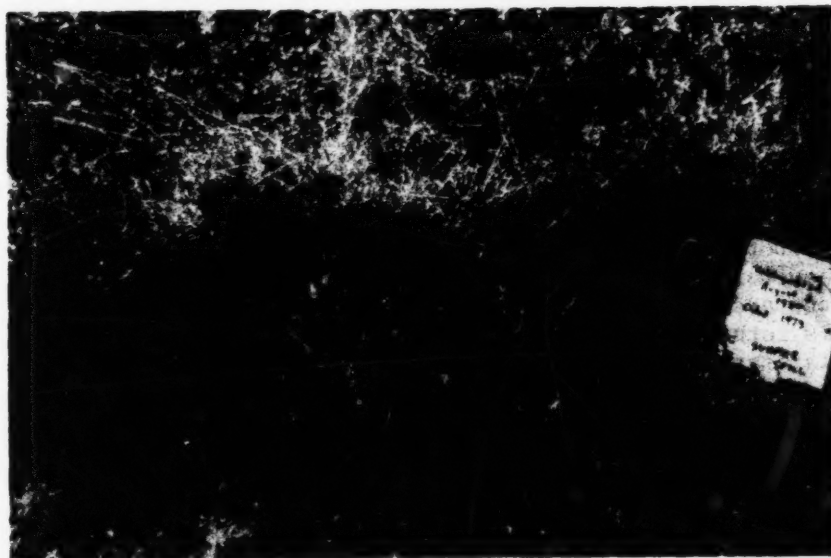


Plate 10. Summer oil spill site in dwarf willow - dwarf birch - lupine tundra site at Tuktoyaktuk in August 1980. Spill made in July 1973. The very vigorous regrowth of the two shrubs can be seen as well as large amounts of the grass Calamagrostis canadensis in fruit. Some bare ground still exists.

Appendix 1. Species list of plants with common names used in the text.

Latin Name	Common Name
<u>BRYOPHYTES</u>	
Equisetum pratense	Meadow-horsetail
Equisetum scorpioides	Dwarf-horsetail/scouring rush
Hylocomium splendens	Feathermoss
Selaginella spp.	Spikemoss
<u>GRASSES/SEDGES</u>	
Calamagrostis canadensis	Reed-bent grass
Calamagrostis purpurascens	Reed-bent grass
Carex bigelowii	Sedge
Carex microglochin	Sedge
Carex podocarpa	Sedge
Carex scirpoidea	Sedge
Eriophorum angustifolium	Cotton-grass
Eriophorum scheuchzeri	Cotton-grass
Eriophorum vaginatum	Cotton-grass
Festuca rubra	Fescue
Oryzopsis spp.	Mountain-rice
Poa arctica	Bluegrass
<u>HERBS</u>	
Andromeda polifolia	Andromeda
Anemone parviflora	Northern anemone
Arctostaphylos rubra	Alpine bearberry
Arctostaphylos uva-ursi	Common bearberry
Empetrum nigrum	Crowberry
Galium boreale	Northern bedstraw
Linnaea borealis	Twinflower
Lupinus arcticus	Arctic lupine
Orchis rotundifolia	Small round-leaved orchid
Pyrola asarifolia	Pink pyrola
Pyrola grandiflora	Large-flowered wintergreen
Pyrola secunda	One-sided pyrola
Rubus chamaemorus	Cloudberry
Stellaria edwardsii	Chickweed

Appendix 1. con.

Latin Name

Common Name

SHRUBS

<i>Alnus crispa</i>	Green alder
<i>Betula glandulosa</i>	Dwarf birch
<i>Betula nana</i>	Birch
<i>Juniperus communis</i>	Ground juniper
<i>Juniperus horizontalis</i>	Creeping juniper
<i>Ledum palustre</i> var. <i>groenlandicum</i>	Labrador-tea
<i>Myrica gale</i>	Sweet gale
<i>Potentilla fruticosa</i>	Shrubby cinquefoil
<i>Rosa acicularis</i>	Prickly wild rose
<i>Salix arbusculoides</i>	Willow
<i>Salix bebbiana</i>	Bebb's willow
<i>Salix glauca</i>	Willow
<i>Salix myrtillifolia</i>	Willow
<i>Shepherdia canadensis</i>	Buffalo berry/ Soapberry
<i>Vaccinium uliginosum</i>	Bog bilberry
<i>Vaccinium vitis-idaea</i>	Mountain cranberry

TREES

<i>Larix laricina</i>	Tamarack/larch
<i>Picea mariana</i>	Black spruce